Delay Tolerant Networking Helps Reducing Age of Information Under Intermittent Connectivity

Leonardo Badia
Dept. Information Engineering
University of Padova
35131 Padua, Italy
email: leonardo.badia@unipd.it

Andrea Munari
Institute of Communications and Navigation
German Aerospace Center (DLR)
Weßling, Germany
email: andrea.munari@dlr.de

***Abstract*—We consider a task-oriented communication between a source and destination for timely status reporting of a monitored system. In spite of a main requirement of low latency, the direct link is affected by intermittent connectivity, which may hinder information freshness, quantified through age of information (AoI). However, the source can leverage delay-tolerant networking (DTN) among other peer nodes. These, in turn, relay the content to the end point, possibly through some similar procedure of spreading the content of interest throughout the entire DTN component. After finding a closed-form expression and a tight asymptotic bound for the service time, we are able to reframe our findings in the context of queueing theory. Specifically, we consider an M/G/1^* queue with the average service time given by our result for the delivery time through the DTN. We show that the relay of information through the DTN is able to counteract problems due to intermittent connectivity, reducing the delivery time by a factor $\ln N/N$. Concerning the resulting average AoI, a proper balance is present between increasing the sampling frequency and increasing the number of nodes in the DTN, which is also discussed.**

***Index Terms*—Age of Information; Task-oriented communication; Delay tolerant networking; Intermittent connectivity.**

I. Introduction

The advent of the Internet of Everything (IoE) in next-generation mobile systems makes it possible to think of collaboration among intelligent terminals for automated content generation to provide task-oriented communications, enabling extremely interactive real-time applications [1]. However, the main challenge in this context is the requirement of up-to-date knowledge about the system under monitoring for proper decision making [2], [3].

Typically, this objective of freshness related to knowledge of the status is quantified by age of information (AoI) [4], a metric defined as the difference between the current time index and the time stamp of the last update received at the control endpoint that is responsible for making the decision. AoI and its evaluation in different systems have received considerable interest in the last decade or so, thanks to its analytical and clear-cut character. For example, many studies have evaluated AoI in the context of queueing theory for different service disciplines and/or queueing policies [5]–[8].

However, the scenario of reference for most studies is that of persistent connectivity, possibly with variable characteristics but with the guaranteed availability of a durable link between the information source and the destination located at the control end point. The presence of intermittent connectivity, which is typical in satellite networks due to the absence of line of sight, fundamentally challenges this assumption and requires the development of alternative communication strategies that ensure timely delivery of data despite disruptions [9]. In this paper, we advocate delay-tolerant networking (DTN) as a solution to this problem. The idea is that many scenarios, while suffering from intermittent connectivity between the source and destination, can also exploit other (still not fully persistent) connections to deliver data [10], [11].

One possible applications of this rationale would be a sensor network connected to a satellite, for environmental monitoring in remote or disaster-prone regions, where traditional infrastructure is absent or unreliable [12], [13]. Sensors deployed across a wide area may only have intermittent line-of-sight access to a satellite that acts as a destination node for data collection. When direct communication to the satellite is not available due to obstructions or orbital position, sensors can opportunistically exchange data with nearby peers. This forms a store-carry-forward architecture, where the data are relayed through the network until they reach a node with satellite visibility [14]. This kind of DTN ensures the eventual delivery of data despite long and variable delays.

Another relevant context is in tactical networks, where mobile ground units or unmanned sensors gather situational data, such as movement of people, terrain conditions, or chemical exposure, and must report to a central command unit [15]. In these high-stakes scenarios, intermittent connectivity arises from physical mobility, interference, or adversarial jamming [16]. Direct links to a command center are rare and unpredictable, so ground units dynamically form an ad hoc mesh network, exchanging data locally until one of them gains connectivity with the control node. This decentralized cooperation reduces latency in data delivery and increases resilience against communication disruptions.

Motivated by the discussion above, in this paper we assess AoI for a satellite communication that leverages a DTN component to improve timely data delivery. This is directly applicable to any satellite-terrestrial scenario, or anywhere the source can benefit from the assistance of peer nodes that may reach the destination earlier. In our analysis, we first consider the delivery time of a DTN-aided communication, given the number N of nodes involved, under the assumption of memoryless contacts among them. We provide both an exact computation and a tight analytical bound that shows the asymptotic decrease in delivery time in N as proportional to $\ln N/N$, in line with the results related to gossiping [17].

Moreover, we reconnect this result with queueing theory by considering an M/G/1* queue (i.e., a preemptive last-come first-served (LCFS) system with memoryless data generation and one server) and compute its average AoI based on the results previously found [18]. While increasing the number of nodes involved in the DTN is always beneficial, we also identify a possible trade-off between this and an increase of the data generation rate to decrease the average AoI. As a result, we show a possible optimization of the number of involved nodes, which also paves the road for possible extensions to specific applications [19], [20].

The rest of this paper is organized as follows. Section II presents the analytical model for the delivery time from a source with intermittent connectivity aided by a DTN relaying towards destination. Section III leverages this model for the average AoI in an M/G/1* queue where the service corresponds to the relaying through the DTN until the destination is reached. We show some interesting numerical results that follow as a consequence in Section IV and we finally conclude in Section V.

II. Impact of Delay Tolerant Networking on Delivery Time

We consider a source autonomously generating task-oriented status updates according to a push paradigm [3], to be delivered to an end point, possibly a satellite or aerial node. However, the communication from the source suffers from intermittent connectivity, and therefore the delivery time through direct connection between source and destination is assumed to be exponentially distributed with parameter β, which may be low and in this case results in slow delivery with large times.

To reduce this delivery time and achieve prompt status reporting, we assume that the source is part of a DTN with N nodes (including the source). A visual representation of the topology considered is shown in Fig. 1. We remark that depiction as a satellite network is done for the sake of graphical rendition, even though this is probably one of the most reasonable scenarios to consider [10], [20]. Moreover, the characterization of the entire network as concerned with the delivery of the task-oriented content implies to transcend traditional pipeline communication schemata and involve a distributed network intelligence in the communication.

In addition to the direct connection to the destination, we assume that any other node of the DTN can be reached with an exponentially distributed time, again with parameter β.[1]

[1]Taking the same value for these two parameters is just done for the sake of a simpler exposition without changing the meaning of the analysis.

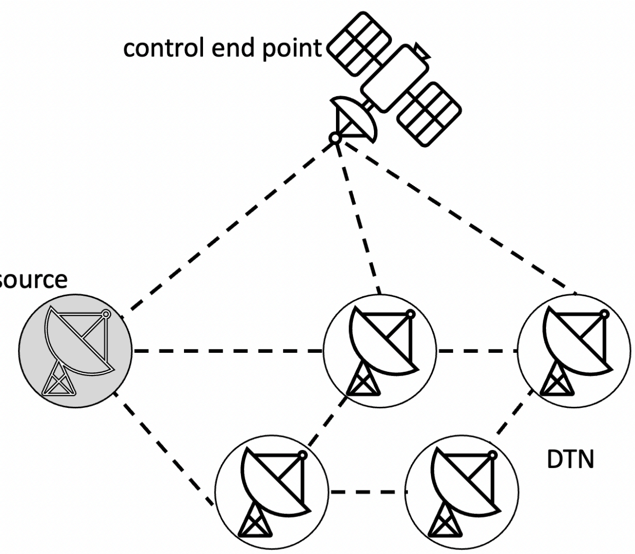

Fig. 1. Considered topology, with the DTN assisting the delivery of information to the control end point. All connections are intermittent and correspond to an exponentially distributed transmission time with parameter β.

This means that if another node of the DTN is reached before the end point, this further node can also attempt to reach the destination; once again, this will happen with the same statistics of the original source and since the entire procedure is memoryless, after reaching another node of the DTN, delivery to the end point takes place with rate 2β. The process is further generalized, since every transition of the chain is memoryless, and, when $j \in \{1, 2, \dots, N\}$ nodes can be reached, it implies a delivery to the end point with rate $j\beta$.

Overall, this can be formalized as the absorption time of a properly defined continuous-time Markov chain [21], [22]. We must note the following. First, the procedure concludes (absorption) once the end destination is reached. Overall, there are $N{+}1$ states, from 1 to N denoting how many nodes in the DTN have received the latest update, plus 0 being an absorbing state describing that the destination is eventually reached. The rate towards state 0 from state $j \in \{1, \dots, N\}$ is equal to $j\beta$. Moreover, transitions between states j and $j+1$ with $j \in \{1, \dots, N{-}1\}$ must account for the number j of nodes that have been reached already and that of nodes who have not been reached yet, which is $N{-}j$.

Thus, the dynamics of the Markov chain is as follows:

- State 0 is absorbing.
- For $k \geq 1$, state k transitions to state 0 with rate $k\beta$ and state $k+1$ (if $k < N$) with rate $k(N-k)\beta$.

Our goal is to compute the expected hitting time T_1, i.e., the time it takes to reach state 0 starting from state 1, with an approximation for large N. For a general N, the generator matrix $\mathbf{Q}$ is constructed as follows:

- $q_{00} = 0$, as state 0 is absorbing.

- For state $k \in \{1, 2, \dots, N-1\}$:

$$\begin{aligned} q_{k,0} &= k\beta, \\ q_{k,k+1} &= k(N-k)\beta, \\ q_{k,k} &= -k(N-k+1)\beta. \end{aligned}$$

- For state N:

$$\begin{aligned} q_{N,0} &= N\beta, \\ q_{N,N} &= -N\beta. \end{aligned}$$

Let T_k denote the expected hitting time from state k to state 0. The recurrence relation for $k \geq 1$ is given by:

$$T_k = \frac{1}{|q_{kk}|} + \frac{q_{k,0}}{|q_{kk}|} T_0 + \frac{q_{k,k+1}}{|q_{kk}|} T_{k+1}. \tag{1}$$

Since $T_0 = 0$ (absorbing state), and substituting the rates:

$$T_k = \frac{1}{k(N-k+1)\beta} + \frac{k(N-k)}{k(N-k+1)} T_{k+1}.$$

For the base case T_N:

$$T_N = \frac{1}{N\beta}.$$

This system of equations can be solved for $T_1, T_2, \dots, T_N$ by properly exploiting recursion, i.e., starting from T_N and going backwards, even though in the end only T_1 is relevant for the analysis that we are interested in here. Alternatively, the Markov chain can be solved with standard procedure of matrix inversion, with a relatively limited computational complexity of $\mathcal{O}(N^3)$. As a side note, although there are more efficient computational methods (pushing the complexity down to $\mathcal{O}(N^\alpha)$ with $\alpha < 3$), these are often unnecessary for practical values of N, and the overall computation is very fast. From the inversion of a proper minor of matrix $\mathbf{Q}$, it is immediate to derive T_1.

Moreover, we can approximate T_1 as N grows. To this end, we iteratively substitute the recurrence relation. For large enough N, the dominant term in the recurrence is:

$$T_1 \approx \sum_{k=1}^{N} \frac{1}{k(N-k+1)\beta}.$$

We then approximate $N - k + 1 \approx N$, giving:

$$T_1 \approx \frac{1}{N\beta} \sum_{k=1}^{N} \frac{1}{k}.$$

The sum $\sum_{k=1}^{N} \frac{1}{k}$ is the N-th harmonic number H_N, which asymptotically behaves as:

$$H_N \sim \ln N + \gamma,$$

where γ is the Euler-Mascheroni constant, which is approximately equal to 0.577216. Substituting this approximation:

$$T_1 \sim \frac{\ln N + \gamma}{N\beta}. \tag{2}$$

This result shows that T_1 decreases as N increases, consistent with the intuition that larger N results in faster absorption due to the increased transition rates. In particular, such a decrease follows a trend of proportionality with $\ln N/N$ in the absorption time. We note that this result matches similar findings about AoI in gossiping systems. Although the model is different in many aspects and our dependence is actually $\ln N/N$, an earlier identification of a logarithmic trend in the number of nodes was already argued by [17].

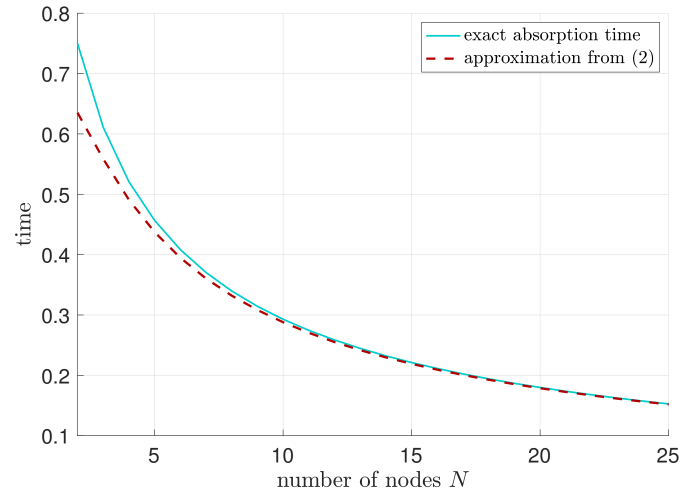

Fig. 2. Solution of the Markov chain vs. approximated formula

Fig. 2 shows a comparison of the approximation in (2) and of the exact form as a function of N. In this evaluation, for numerical convenience, we set $\beta = 1$. We compare the exact approach of solving the Markov chain to obtain the absorption time, with the lower bound of (2). It is clearly visible that already with N=10 nodes the approximation is very good and is basically indistinguishable for larger values of N.

III. Age of Information Analysis

We now extend the result found in the previous section to analyze AoI, a performance metric that quantifies the freshness of information at a receiver. At any time t, AoI is defined as the difference between the current time and the timestamp of the most recently received update. Formally, if at time t the most recent update received was generated at time $u(t)$, then the instantaneous AoI $\delta(t)$ is:

$$\delta(t) = t - u(t). \tag{3}$$

This metric captures how stale the information is at the destination, which is relevant in systems that monitor physical processes in real time. It is also connected to queueing theory, as update packets often travel through a network modeled as a queueing system. The characteristics of the queue in terms of waiting time, service discipline, and scheduling policy, directly impacts the evolution of AoI over time. In our case, more than the processing at the end point, which can be taken as negligible or with a fixed delay, the relevant part is the time taken to reach the destination possibly through the DTN.

Thus, we consider a source that generates status updates according to a Poisson process of intensity λ. This source exploits a DTN with a total of N nodes, including the source itself, to reach an end destination with intermittent connectivity.

Moreover, we take that status updates are handled according to an LCFS policy with preemptive service. This means that when a status update is received at the destination, it preempts any other update currently being processed; in other words, older updates are discarded. This actually makes sense if the overall objective is to minimize the average AoI, as is likely to be the case for emergency or tactical scenarios. We remark that this prioritization also allows us to ignore the coexistence of multiple updates of different epochs in the DTN. As long as the simultaneous presence of multiple updates does not cause, e.g., collisions or congestion, one can simply track the most recent updates [8], and each node of the DTN can adopt the same discarding approach of keeping the most recent update.

Reference [18] contains many closed-form expressions for the average AoI in queueing systems as a function of the generation rate λ and service rate μ, where for single-server systems it must hold that $\lambda < \mu$. We remark that if $N{=}1$, i.e., there is no assistance to the delivery from the DTN, we simply get what [18] denotes as an M/M/1* queue (i.e., an M/M/1 queue with preemption), where $\beta = \mu$.

If $N{>}1$, then we get a more general M/G/1 queue with preemptive service policy, denoted as M/G/1*. In that case, we can trace back the results of the literature and extend the consideration to the case where $\mu = 1/T_1$ as derived in the previous section. Thanks to the independence of update generation and DTN relaying, we can simply treat the entire process of reaching the destination as an independent service, albeit no longer memoryless, since its duration actually depends on how many nodes in the DTN have been reached by the update.

Still, the same approach of [18] remains, so that the average AoI Δ in such a system can be computed as

$$\Delta = \frac{1}{\lambda} + \frac{1}{\mu} = \frac{1}{\lambda} + T_1 \,, \tag{4}$$

where AoI is obtained as the sum of the absorption time with the average inter-generation time of updates $1/\lambda$.

This actually shows that there are two components in the average AoI. Although the average inter-generation time can be reduced with intense status sampling by the generating source, the value of T_1 is due to network connectivity and cannot be directly controlled by the source. This also justifies our use of the DTN paradigm to lower T_1.

As a side remark, even though the choice of an M/G/1* is possibly justified by the willingness to achieve a low AoI, and this preemptive queue is the one performing best in this sense among elementary queues, the quantitative evaluations derived in the following apply more or less in the same way to any kind of similar queue, albeit with more complicated derivations. Thus, we stick with the M/G/1* that combines the advantage of a clear analytical setup with the illustrative purpose of a clear separation between the contribution due to the interarrival time and that due to the absorption time in the Markov chain.

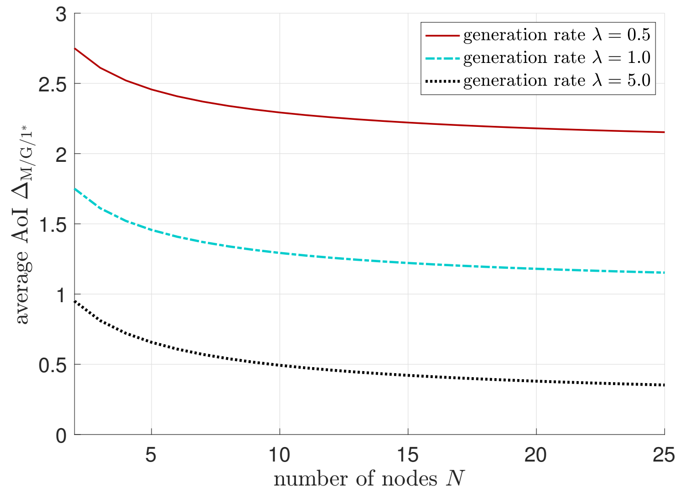

Fig. 3. Average AoI of M/M/1* queue vs. number of nodes in the DTN, for different values of data generation rate λ.

IV. Results

The first immediate result considers the direct evaluation of (4) for different values of λ and N, the latter ultimately determining T_1. Once again, we set $\beta = 1$ but all the results can be re-scaled accordingly if needed (in other words, the plots show the values normalized to a unit β). This evaluation is shown in Fig. 3, and it is evident that N decreases the average AoI. However, the extent of such a decrease depends heavily on λ. When the average inter-update time is low, T_1 becomes the bottleneck and therefore decreasing it significantly reduces AoI. Conversely, for a low λ, the relative advantage of decreasing T_1 is less pronounced. For numerical validation, it is possible to see that already having $N{=}25$ reduces the average AoI to the only contribution $1/\lambda$.

This suggests that a low average AoI should be obtained by decreasing both parts of (4), also including $1/\lambda$, that is, specifically adopting a frequent sampling of the process of interest, as well as including as many nodes as possible in the DTN. However, cost reasons suggest that these two actions cannot be forced indefinitely. Moreover, one can argue that there must be a limit on the number of operations that can be performed, e.g., for energy reasons [9], [21].

To investigate this aspect, consider the following way to formalize the tradeoff. Assume that N nodes are available for relaying in the DTN, but this potentially causes an increase in the transmission rate by a factor N. Intuitively speaking, a comparable resource consumption can be achieved by using only $N/2$ nodes but doubling the sampling frequency. In reality, this comparison is not this direct and simple, but rather depends on the hardware of the nodes and the kind of underlying process. In fact, the balance between the measurement and transmission costs is not this simple [2], [23] and should be parametrized with a more general approach.

Still, for the sake of exposition, consider the following modeling. We define a tuning parameter ω that regulates how much of the resources are used to decrease the delivery time

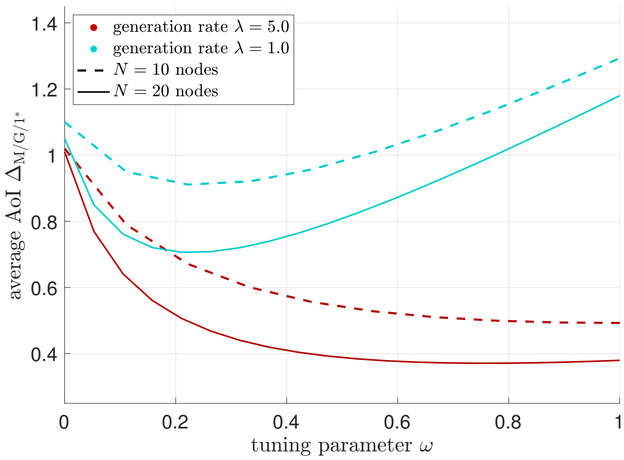

Fig. 4. Average AoI of M/M/1* queue for different values of the tuning parameter ω, for different numbers of nodes in the DTN and data generation rates λ.

T_1 to the destination versus how much is used to increase λ. In other words, if N nodes are available in the DTN, we consider $n = \omega(N-1)$ of them to assist the source [19], thereby decreasing the delivery time T_1 with a $\ln n/n$ proportionality, and conversely we increase λ by a factor ω. If needed, a further scaling between these resource usages can also be included, but this would ultimately correspond to simply considering a different value of λ in the graphs.

Fig. 4 shows the resulting average AoI for different values of λ, plotted in different colors, and also N, where dashed lines refer to the case with $N{=}10$ nodes, while solid lines show the trend for $N{=}20$ nodes. Once again, a normalized $\beta = 1$ is considered. The figure shows that when λ is high, resulting in a shorter average interval between updates, the effect of the tuning parameter is in favor of using the majority of the nodes in the DTN, although it should be noted that the actual minima of the curves lie before $\omega = 1$.

However, even when λ is smaller and therefore the inter-update times are longer on average, it is sensible to consider an intermediate value of ω between 0 and 1, i.e., to properly balance how many nodes to put in the DTN versus how often to sample the environment. When N is increased, it is also evident how the overall average AoI decreases, as a high number of nodes in the DTN gives more freedom towards a timely delivery of the status update.

V. Conclusions and Future Work

We presented an analytical model for the delivery time of autonomously generated status updates whose communication to the destination is intermittently connected, but also aided by a DTN comprising a total of N nodes with memoryless contacts. All nodes on the DTN can reach the destination with similar intermittent connectivity. This creates an interesting extension to the average AoI computed using queueing theory, as more resources can be devoted to more frequent status sampling or stronger communication within the DTN [18].

Ultimately, the choice on where to put extra transmission resources poses a trade-off that shows how frequent status detection and relaying through the DTN are to be harmonized to successfully diminish the average AoI and execute system control with sufficient information freshness [7]. A possible extension would be, instead of deriving average values through queueing theory, to enact a transmission scheduling, to further alleviate the problem of intermittent connectivity through an opportunistic approach that checks when the channel is available [9]. Additionally, strategic decision making of the involved nodes can be included for participatory collaboration [23].

Further extensions of the present analysis are possible, in particular considering different topologies and diffusion schemes in the DTN. For instance, instead of memoryless encounters, specific routing towards better relays can lower the delivery time even further [24]. In addition, one can also consider a more mixed satellite-terrestrial network; as of now, the model implies only one satellite node as the destination, but all the DTN connections are terrestrial. However, multiple satellites can also be considered [10], with the added twist that the increase in the delivery rate is no longer memoryless but follows a deterministic pattern, corresponding to the movements of the satellites in the constellation.

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References

[1] L. Guo, W. Chen, Y. Sun, B. Ai, N. Pappas, and T. Quek, "Diffusion-driven semantic communication for generative models with bandwidth constraints," *IEEE Trans. Wireless Commun.*, vol. 24, no. 8, pp. 6490–6503, 2025.

[2] Ó. Seijo, J. A. López-Fernández, and I. Val, "w-SHARP: Implementation of a high-performance wireless time-sensitive network for low latency and ultra-low cycle time industrial applications," *IEEE Trans. Ind. Informat.*, vol. 17, no. 5, pp. 3651–3662, 2020.

[3] P. Agheli, N. Pappas, P. Popovski, and M. Kountouris, "Integrated push-and-pull update model for goal-oriented effective communication," *IEEE Trans. Commun.*, 2025, early access.

[4] S. Kaul, M. Gruteser, V. Rai, and J. Kenney, "Minimizing age of information in vehicular networks," in *Proc. IEEE Int. Conf. Sensing Commun. Netw. (SECON)*, 2011, pp. 350–358.

[5] M. Moltafet, M. Leinonen, and M. Codreanu, "On the age of information in multi-source queueing models," *IEEE Trans. Commun.*, vol. 68, no. 8, pp. 5003–5017, 2020.

[6] Y. Inoue, H. Masuyama, T. Takine, and T. Tanaka, "The stationary distribution of the age of information in FCFS single-server queues," in *Proc. IEEE Int. Symp. Inf. Theory (ISIT)*, 2017, pp. 571–575.

[7] J. P. Champati, H. Al-Zubaidy, and J. Gross, "Statistical guarantee optimization for AoI in single-hop and two-hop FCFS systems with periodic arrivals," *IEEE Trans. Commun.*, vol. 69, no. 1, pp. 365–381, 2020.

[8] F. Chiariotti, O. Vikhrova, B. Soret, and P. Popovski, "Age of information in multihop connections with tributary traffic and no preemption," *IEEE Trans. Commun.*, vol. 70, no. 10, pp. 6718–6733, 2022.

[9] L. Badia and A. Munari, "Satellite intermittent connectivity and its impact on age of information for finite horizon scheduling," in *Proc. IEEE Adv. Sat. Multimedia Syst. Conf. Signal Proc. Space Commun. (ASMS/SPSC)*, 2025, pp. 1–8.

[10] M. Xu, M. Jia, Q. Guo, and T. De Cola, "Delay-sensitive and resource-efficient VNF deployment in satellite-terrestrial networks," *IEEE Trans. Veh. Technol.*, vol. 73, no. 10, pp. 15 467–15 482, 2024.

[11] L. Badia and M. Scalabrin, "Stochastic analysis of delay statistics for intermittently connected vehicular networks," in *Proc. European Wirel. Conf.*, 2014.

[12] T. Z. Ornee, M. K. C. Shisher, C. Kam, and Y. Sun, "Context-aware status updating: Wireless scheduling for maximizing situational awareness in safety-critical systems," in *Proc. IEEE Military Commun. Conf. (MILCOM)*, 2023, pp. 194–200.

[13] Y. Li, Y. Xu, Q. Zhang, and Z. Yang, "Age-optimized multihop information update mechanism on the LEO satellite constellation via continuous time-varying graphs," *IEEE Internet Things J.*, vol. 10, no. 8, pp. 7189–7203, 2022.

[14] T. Kellermann, R. P. Centelles, and A. Calveras, "UE context dissemination in sparse LEO constellations for 5G/6G cellular IoT in store and forward operation," *IEEE Open J. Commun. Soc.*, vol. 6, pp. 2539–2555, 2025.

[15] I. Cosandal and S. Ulukus, "Timely multi-goal transmissions with an intermittently failing sensor," in *Proc. IEEE Military Commun. Conf. (MILCOM)*, 2023, pp. 176–181.

[16] G. D. Nguyen, S. Kompella, C. Kam, J. E. Wieselthier, and A. Ephremides, "Information freshness over an interference channel: A game theoretic view," in *Proc. IEEE Int. Conf. Comp. Commun. (INFOCOM)*, 2018, pp. 908–916.

[17] P. Mitra and S. Ulukus, "Timely opportunistic gossiping in dense networks," in *Proc. IEEE Int. Conf. Comp. Commun. (INFOCOM) Wkshps*, 2023, pp. 1–6.

[18] R. D. Yates, Y. Sun, D. R. Brown, S. K. Kaul, E. Modiano, and S. Ulukus, "Age of information: An introduction and survey," *IEEE J. Sel. Areas Commun.*, vol. 39, no. 5, pp. 1183–1210, 2021.

[19] F. Chiariotti and L. Badia, "Strategic age of information aware interaction over a relay channel," *IEEE Trans. Commun.*, vol. 72, no. 1, pp. 101–116, 2024.

[20] H. Zarini, S. M. Kazemi, M. Sookhak, E. Uysal, and S. Chatzinotas, "Age of information in LEO satellite communications supported by BD-RIS," in *Proc. IEEE Int. Conf. Commun. (ICC)*, 2025, pp. 1–6.

[21] N. Michelusi, K. Stamatiou, L. Badia, and M. Zorzi, "Operation policies for energy harvesting devices with imperfect state-of-charge knowledge," in *Proc. IEEE Int. Conf. Commun. (ICC)*, 2012, pp. 5782–5787.

[22] N. Akar and E. O. Gamgam, "Distribution of age of information in status update systems with heterogeneous information sources: An absorbing Markov chain-based approach," *IEEE Commun. Lett.*, vol. 27, no. 8, pp. 2024–2028, 2023.

[23] A. Buratto, E. Guerra, M. Miozzo, P. Dini, and L. Badia, "Energy minimization for participatory federated learning in IoT analyzed via game theory," in *Proc. Int. Conf. Artif. Intell. Inf. Commun. (ICAIIC)*, 2024, pp. 249–254.

[24] V. Mancuso, L. Badia, P. Castagno, M. Sereno, and M. A. Marsan, "Effectiveness of distributed stateless network server selection under strict latency constraints," *Comp. Netw.*, vol. 251, p. 110558, 2024.